Collaborative Research UTIG and USGS: Towards an integrated understanding of late Holocene fault activity in western Puerto Rico: Onland scarp mapping and fault trenching

Final Project Report

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Investigations undertaken

Regional tectonic setting of study area. The island of Puerto Rico is located within a complex plate boundary zone between the North American and Caribbean plates (Mann *et al.*, 1998; DeMets *et al.*, 2000). The dominant motion along the plate boundary combines strike-slip, thrusting, and normal faulting. Because nearly two-thirds of the plate boundary in the Puerto Rico-Virgin Islands area is submerged and inaccessible for detailed field studies, present-day neotectonic models rely heavily on teleseismic studies (Deng and Sykes, 1995, McCann, in press), GPS-based geodetic studies (*e.g.,* Jansma *et al.*, 2001) and marine geophysical surveys including sonar mapping, seismic profiling, and potential field mapping methods (Dillon *et al.*, 1996; Grindlay *et al.*, 1997; van Gestel *et al.*, 1998; Dolan *et al.*, 1998).

These previous studies suggest that the island of Puerto Rico is in the process of slowly detaching at a rate of about 5 mm/yr from the island of Hispaniola to the west (Jansma, *et al.*, 2001) (Fig. 1A). This boundary is potentially as wide as 150 km, but most data sets, including GPS-based geodetic results, indicate that the boundary is centered within westernmost Puerto Rico and the Mona Passage, the marine strait separating Puerto Rico and Hispaniola (Fig. 1A). The deepest part of the Mona Passage is the Mona rift, a late Quaternary rift produced by about 5 km of extension (Fig. 1B). Regional deformation in this area, including abundant normal faulting in the Mona Passage and western Puerto Rico appears to be related to the oblique collision of the Bahama carbonate platform with Hispaniola to the west of Puerto Rico (Fig. 1C). This oblique collision has pinned or impeded the eastward motion of Hispaniola relative to North America and the Bahama Platform and has produced a complex zone of rotation and extension in the area of the Mona Passage and western Puerto Rico. This Miocene-recent rotation/extension history of Puerto Rico contrasts with the coeval history of thrusting, left-lateral strike-slip faulting and topographic uplift observed to the west in the Hispaniola-Bahamas oblique collision zone (Mann *et al.*, 1998, Prentice *et al.*, in press).

Previous marine geophysical studies of the Mona Passage indicate several sets of active, large displacement, normal faults (*e.g.,* van Gestel *et al.*, 1998) (Fig. 1B). The presence of these faults is consistent with GPS results indicating that northwestern Puerto Rico is moving at a rate of 16.9 ± 1.1 mm/yr relative to the North America plate (Jansma *et al.*, 2001) (Fig. 1A). This motion is relatively faster than rates observed east of the Mona rift in Hispaniola and is consistent with pinning of Hispaniola by the Bahama collision, extensional opening of the Mona rift and right-lateral strike-slip motion along major, west-northwest-striking faults in Puerto Rico (*i.e.,* Cerro Goden and Great Southern Puerto Rico faults) (Fig. 1A).

Seismic hazards in Puerto Rico. Puerto Rico is one of the most densely populated areas of the western hemisphere with a land area of approximately 7,000 km^2 and a highly urbanized and rapidly growing population of over 3.5 million inhabitants. Much of the population is concentrated in the coastal cities of San Juan on the northeast coast of the island, Mayaguez on the west coast, and Ponce on the south coast (Fig. 1A). Rapid development of the west coast near Mayaguez has accompanied the recent completion of a major highway connecting San Juan and Mayaguez and Mayaguez to the Lajas Valley in the southwestern part of the island (Fig. 2A).

Western Puerto Rico and the adjacent Mona Passage is the most seismically active region of Puerto Rico (Fig. 1A). During the past five years, over 70 earthquakes with a magnitude of 3 or greater have been recorded by the local seismic network in the western region of Puerto Rico (McCann, in press). Moreover, several large to great historical earthquakes have occurred within the nearby Puerto Rico trench. Ascencio (1980) has compiled historical evidence for at least 40 strong events originating in the Mona Passage or northwest Puerto Rico between 1524 to 1958.

Onland studies of active faults. Investigations of onland faulting in Puerto Rico have been limited and with one notable exception (Geomatrix Consultants, 1988) have been ancillary to mapping of pre-Quaternary bedrock units that cover most of the island (*e.g.,* Glover, 1971, and published USGS geologic quadrangle maps such as McIntyre, 1971). The Great Southern Puerto Rico fault zone crosses Puerto Rico trending west-northwest (Glover, 1971) and appears to be continuous with the Cerro Goden fault zone of northwestern Puerto Rico (McIntyre, 1971; Moya and McCann, 1991) (Fig. 1A). This fault zone was active during the Tertiary and record predominantly thrust and left-lateral displacement (Glover, 1971; Erickson *et al.*, 1991). Field evidence for motion along both faults since the Miocene is sparse, although Geomatrix Consultants (1988) found several areas of likely late Quaternary deformation in south-central Puerto Rico (Fig. 2A).

Shallow seismicity on the island of Puerto Rico is concentrated in the southwest corner of the island (McCann, in press) (Fig. 2A). Southwestern Puerto Rico is characterized by numerous northwest to east-west-striking faults and lineaments in Pliocene and older rocks. Previous workers (*e.g.,* Joyce *et al.*, 1987) have likened the fault pattern and resultant topography to basin and range structure including the topographically prominent Lajas Valley (Fig. 2A).

These bedrock faults may be analogous to the horst and graben features mapped in the Mona Passage by van Gestel *et al.* (1998) and by us in our 2000 offshore survey (Grindlay, *et al.*, 2000; Grindlay *et al.*, this volume) (Fig. 1A). In some cases, we can show late Holocene faulting but not in as widespread a pattern as topographic, bedrock relief would suggest. Interpretation of high-resolution reflection profiles collected by Meltzer (1998) across the southern margin of the Lajas Valley of southwestern Puerto Rico suggests offsets of reflectors correlated to Quaternary lacustrine sediments of Laguna Cartagena and its predecessor lakes (Fig. 2A). Meltzer (1998) interpreted the offsets as late Quaternary in age and oblique-normal and transtensional in origin.

Field results of this study

Initial NEHRP field study of active faults in 2000. To provide basic information on active faults in western Puerto Rico, Carol Prentice and I conducted field studies in January and Februrary of 2000 aimed at identifying onshore active faults. We identified two active faults, which we describe in detail in the text and figures of this report. Prior to our study, no late Quaternary faults had been documented in or near Puerto Rico by Joyce *et al.* (1987), Geomatrix (1988) or other previous studies.

South Lajas fault study, Lajas Valley, southwestern Puerto Rico. The Lajas Valley has long been suspected as a possible area of active faulting because of its prominent east-west topographic expression, linear mountain fronts, and closed topographic depressions within the valley (*e.g.,* Joyce *et al.*, 1987) (Fig. 2A). Using the 1936, 1:18,500 scale photographs, we identified the first late Quaternary fault scarp in the Puerto Rico area (Fig. 2B, C). The South Lajas fault forms a 5 km-long scarp cutting an alluvial fan on the southeastern side of the topographically prominent Lajas Valley near Boqueron (Fig. 2B). We excavatated a shallow test trench across the scarp to determine whether it is the result of recent fault slip or some other geomorphic process (Fig. 3A). The trench exposed two fault zones, about 1 m apart, that disrupt Quaternary alluvial fan deposits (Fig. 3A). Relations indicate normal faulting, valley-side down, with a component of strike-slip motion, though we could not determine whether the horizontal component of displacement is right- or left-lateral. The two fault zones terminate at different stratigraphic horizons, indicate at least two surface-rupturing events. Radiocarbon analyses of organic material suggest that surface ruptures occurred during the last 7500 years (Fig. 3B). The earlier event occurred between 5650 and 7550 years B.P. The younger event occurred post 5040 calendar years B.P., but no minimum age has yet been established. The paleoseismology of this fault, including its minimum age of fault displacement, could be improved by additional trenching at sites we identified near the trench shown in Figure 3A.

Fault scarp adjacent to Laguna Cartagena, southwestern Puerto Rico. We identified a low scarp in this region that is along strike of the South Lajas fault trenched at the site shown in Figure 3A. The scarp appears to have been modified as a shoreline feature of the Laguna Cartagena which was largely drained in the 1950s (Fig. 2D). This is an ideal site for future trench studies because of its lacustrine stratigraphy and probable abundance of fine-grained organic matter for radiocarbon dating.

Eastward extent of the South La Lajas fault. Reconnaissance work suggests that this fault may be part of a roughly east-west-striking fault system that extends 50 km from our trench site in the western Lajas Valley to the city of Ponce in south-central Puerto Rico. On Figure 2A, we have attempted to summarize our best understanding of known and suspected areas of active faulting in an east-west swath parallel to the Lajas Valley and extending 50 km to the east to the Ponce area. Site 1 is our initial trench site shown in Figures 2B and C; site 2 is the promising trench site near Laguna Cartagena shown in Figure 2D. Site 3 on Figure 2A is described by Geomatrix Consultants (1988) as an area of faulted Quaternary gravels along the east-west Madrigal fault zone. Sites 4 and 5 are prominent fault valleys cutting Pliocene carbonate rocks of the Ponce Formation to the west and north of the city of Ponce (Fig. 2A). These bedrock faults correspond in some cases to lineaments in alluvium that we identified on 1936 photographs. We investigated some of these lineaments but were unable to document evidence of Quaternary fault activity because of large-scale cultural modification of these areas. Sites 6 and 7 are seafloor scarps of probably Holocene age identified in our offshore survey in 2000 (Grindlay *et al.*, 2000).

Cerro Goden fault study, Mayaguez area, western Puerto Rico. We mapped along the Cerro Goden fault zone which parallels a major, linear, abrupt mountain front (La Cadena de San Francisco) within 10 km of the city of Mayaguez (Fig. 4A, location of Figure 4A in Figure 1A). The fault extends offshore to the west in the direction of the Mona rift shown in Figure 1B (Grindlay *et al.*, 2000; Grindlay *et al.*, this volume). We have not yet investigated the continuation of the Cerro Goden fault zone to the southeast of the area shown on Figure 4A. Moya and McCann (1991) have postulated that the Cerro Goden fault is directly continuous with the Great Southern fault zone of south-central Puerto Rico as shown on Figure 1A (Glover, 1971; Erikson *et al.*, 1991).

Using both 1:18,500 scale air photographs taken in 1936 and 1:40,000 scale photographs taken by the USDA in 1994, we identified geomorphic features suggestive of Quaternary fault movement on the Cerro Goden fault zone including aligned and right-laterally deflected drainages, right-laterally offset terrace risers, and mountain-facing scarps (Fig. 4B, C). A much larger right-lateral deflection of 3.65 km is also present in the course of the Rio Anasco and is shown on Figure 4A. Right-lateral offset at all scales along this fault is consistent with its late Quaternary regional tectonic setting shown in Figure 1A and discussed above.

The fault is similar to the Septentrional fault we studied in the Dominican Republic (Prentice *et al.*, 1993; Mann *et al.*, 1998; Prentice *et al.*, in press) because the active trace is about 500 m south of the prominent mountain front. In a salient of the mountain front, the active trace is in alignment with a linear bedrock fault mapped by McIntyre (1971) and named the Cerro Goden fault in the Central La Plata quadrangle. The Cerro Goden fault juxtaposes outcrops of two dissimilar Cretaceous formations for a distance of about 7 km along its length (Fig. 4A).

Promising sites for future paleoseismic studies are indicated on the blowups of the 1936 aerial photographs in Figures 4B and C. One site is across a right-lateral offset of a small terrace in the Anasco Valley (Fig. 4B) which is along the projection of the bedrock scarp seen to the east (Fig. 4C). The other site is farther east across a lineament on a fluvial terrace of the Rio Anasco that appears to be structurally controlled by the fault trace (Fig. 4C). This linear terrace edge is also in alignment with the bedrock fault and a lineament that was mapped in detail by McIntyre (1971) and shown on Figure 4C.

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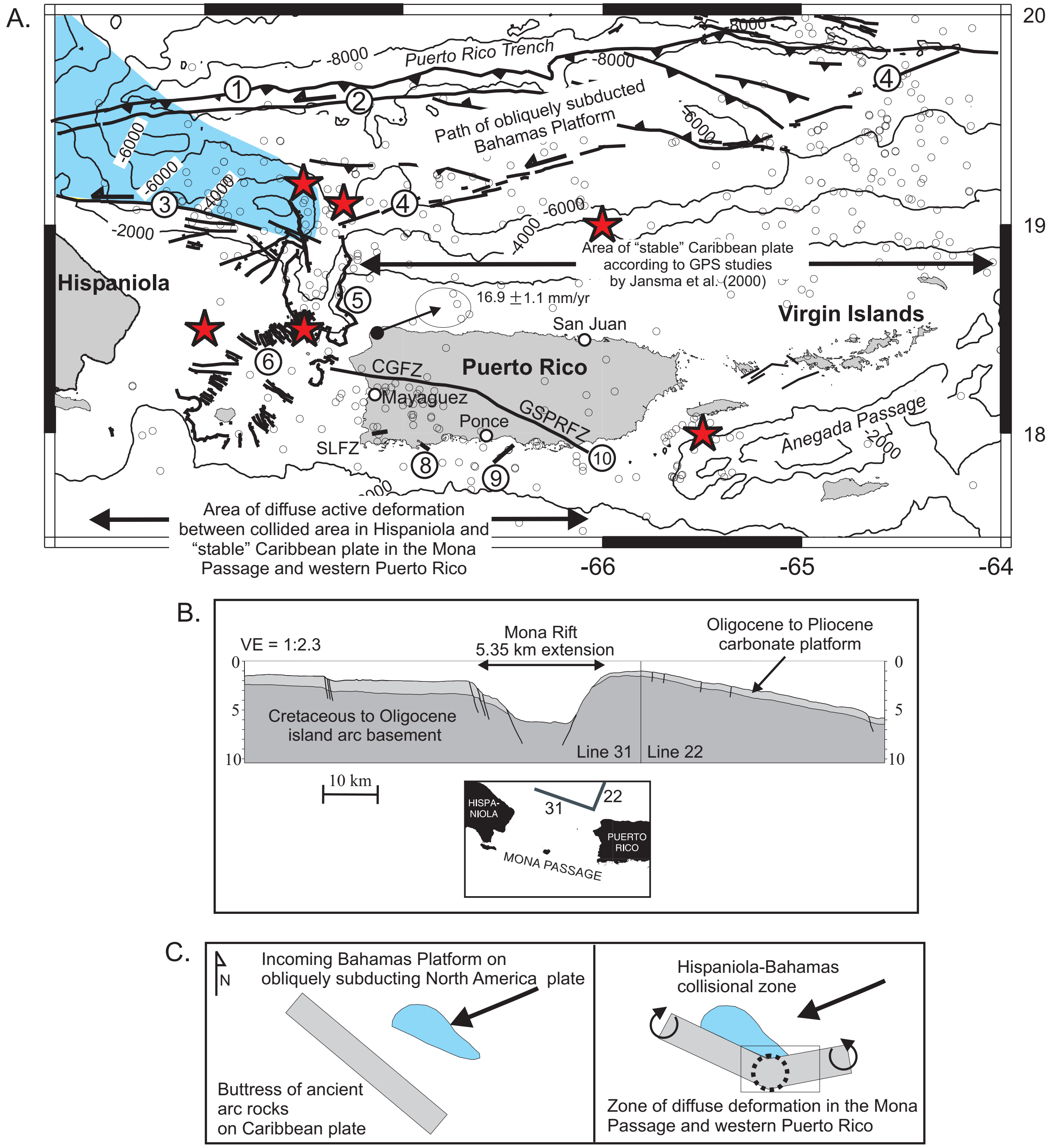
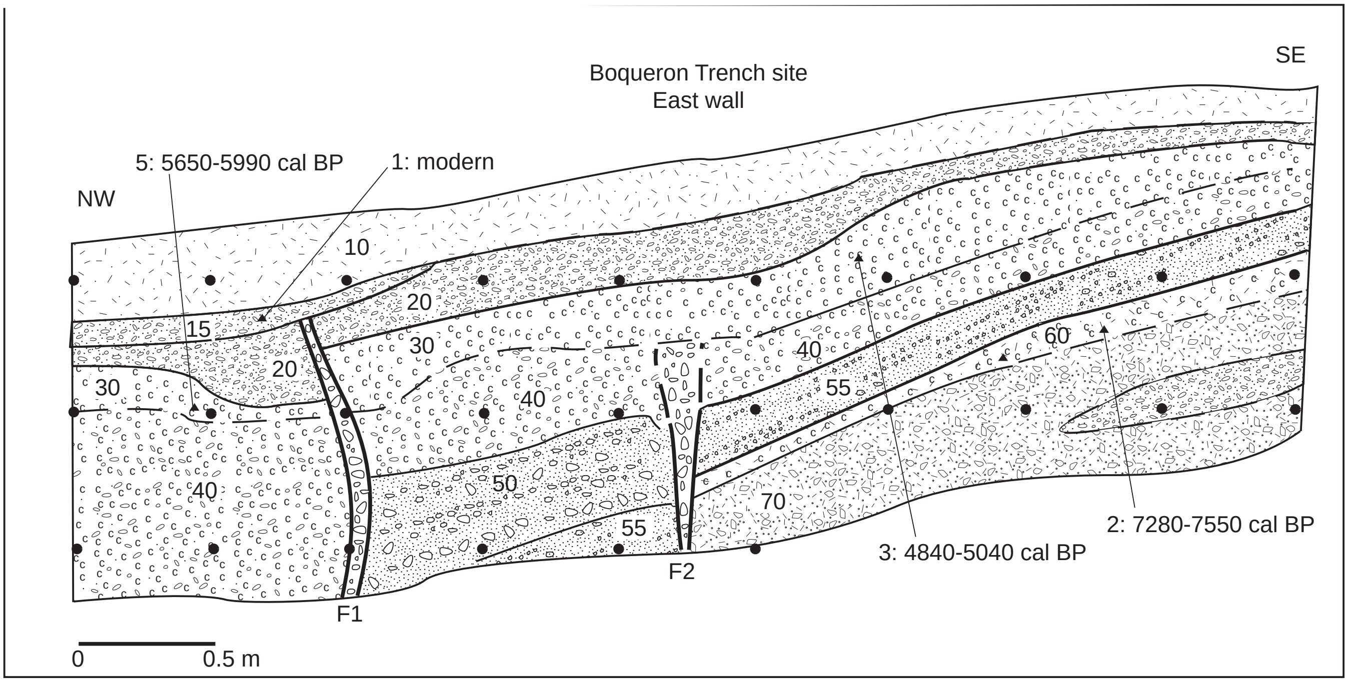


Figure 1. A. Bathymetric and tectonic map of the Puerto Rico-Virgin Islands area showing our present understanding of the regional tectonic setting of major, possibly seismogenic faults indicated by numbers and abbreviations: **1** = Puerto Rico trench; **2** = North Puerto Rico slope fault zone; **3** = Septentrional fault zone; **4** = South Puerto Rico slope fault zone; **5** = eastern bounding fault of the Mona rift; **6-10** = areas of seafloor faults mapped by Grindlay et al. (1997; 2000; this volume); **CGFZ** = Cerro Goden fault zone; **GSPRFZ** = Great Southern fault zone; **SLFZ** = South Lajas fault zone. Open circles are earthquake epicenters from 1973-1999 occurring at depths < 30 km. Stars represent large magnitude historical earthquakes. GPS data from the northwest corner of Puerto Rico is from Jansma et al. (2001). Shaded area to northwest represents subducted (Mona block) and non-subducted area of the Bahama carbonate platform. **B.** Cross section of the post-early Pliocene Mona rift based on single-channel seismic lines from van Gestel et al. (1998). **C.** Schematic diagram illustrating regional effect of oblique Bahama collision on the tectonics of the area of the Mona Passage and western Puerto Rico. Hispaniola has a prominent record of post-middle Miocene convergence while Puerto Rico's Neogene record is dominated by diffuse extension and strike-slip possibly related to the rotation and detachment of Puerto Rico accompanying the late Miocene-recent Bahamas-Hispaniola collisional event.

Figure 2. A. Topographic map of southwestern Puerto Rico showing the location of the South Lajas fault (black line labelled 1), the South Laguna Cartagena fault (number 2), prominent lineaments in bedrock (numbers 3, 4, 5), and zones of mapped seafloor scarps of probable Holocene age mapped by Grindlay et al. (2000) and Grindlay et al. (This volume) (numbers 6 and 7). **B**. 1936 aerial photograph showing the South Lajas fault crossing an alluvial fan on the southern side of the Lajas Valley. Trench site shown in C and in Figure 3A is indicated.. **C**. We excavated a 2-meter-deep trench across this scarp exposing two fault zones, about 1 meter apart, that disrupt the alluvial deposits (cf. Figure 3A for log). **D**. View looking north at a 1.5 m high, valley-facing, probable fault scarp parallel to the former lake edge of Laguna Cartagena. This lake is now largely drained in a closed topographic depression in the Lajas Valley. We have named this fault the South Laguna Cartagena fault and recommend it as a site for future trenching.

A.



B. CALCULATED DATES FROM ^{14}C ANALYSIS OF CHARCOAL, SOUTH LAJAS FAULT, PUERTO RICO

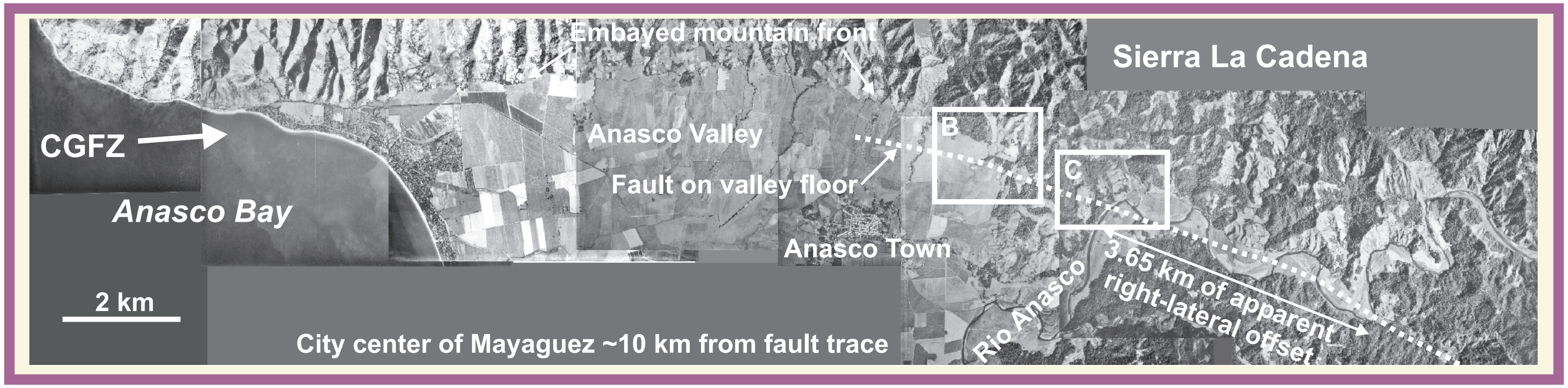
NO.	Sample	Delta 13C (o/oo)	C14 age* (yr B.P.)	Calibrated years BP† (2-sigma)	Probability distribution
1	AA-36450	-21.8	Post-bomb	0	
2	AA36451	-22.9	6495±60	7280-7550	7280-7500 .97 7540-7550 .03
3	AA-36452	-23.5	4360 ±45	4840-5040	4840-5040 1.0
5	AA-36454	-22.0	5100 ±80	5650-5990	5650-5990 1.0

* Conventional radiocarbon ages reported by University of Arizona. Calculations assume a Libby half-life (5568 yr). Uncertainties are 1 standard deviation counting errors.

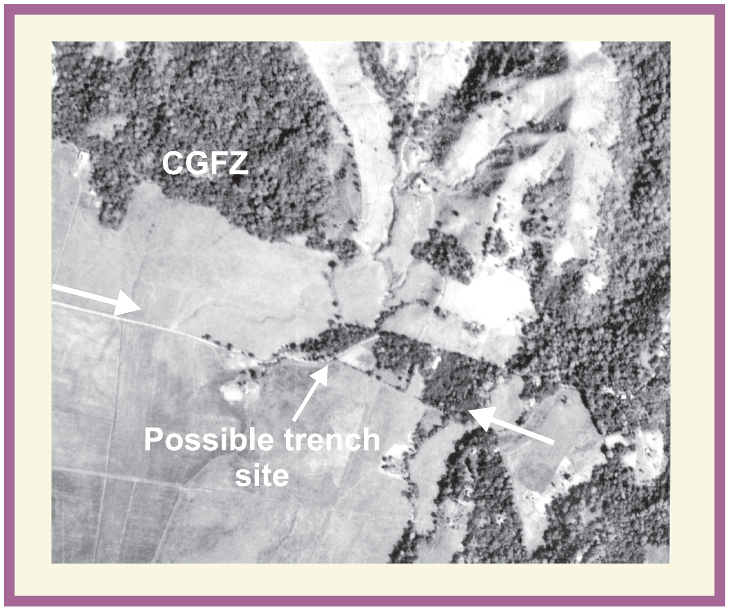
† Dendrochronologically calibrated, calendar age ranges from CALIB Rev. 4.2, Method B, 2 standard deviation uncertainty. Rounded to nearest decade.

Figure 3. A. Log of trench across South Lajas fault zone showing slip on two fault zones, valley-side (north side) down, with a component of strike-slip motion. The two fault zones terminate at different stratigraphic horizons and indicate at least two surface-rupturing events. The northern fault, labeled F1 on the trench log, extends through units 30 and 20, but does not break unit 15. The southern fault, labeled F2, extends through unit 50, and possibly through unit 40, but does not break unit 30. These are the first documented Holocene faults in Puerto Rico. **B**. Table showing results of radiocarbon analyses of organic material suggesting that the two faults shown on the log ruptured during the last 7500 years. The earlier event is between 5650 and 7750 years B.P. The younger event occurred post 5040 calendar years B.P., but no minimum age has yet been established.

A.



B.



C.

Figure 4. A. Map of the Cerro Goden fault zone (CGFZ) along the northern edge of the Anasco Valley made from a mosaic of 1936 aerial photographs (original scale 1:18,500). Large arrows indicate trace of fault along the embayed mountain front of the Sierra La Cadena and extending into Anasco Bay where Holocene strands of the fault have been mapped by Grindlay et al. (2000). The Rio Anasco displays 3.65 km of apparent right-lateral offset by the trace of the CGFZ. Boxes indicate blowups of aerial photos shown in B and C. **B**. Possible trench site on a stream terrace showing an apparent right-lateral offset. Despite cultural overprinting, the site was in an open field at the time of our field work in 2000. **C**. Possible trench site on a terrace of the Rio Anasco showing a faint scarp in 1936. The lineament is in direct alignment with the bedrock exposure of the fault to the east and west of the proposed trench site. Note bedrock scarp along the mapped trace of the Cerro Goden fault zone n the hills separating the two possible trench sites.

Non-technical Summary: Final Project Report

Collaborative Research: UTIG and USGS: Towards an integrated understanding of late Holocene fault activity in western Puerto Rico: Onland scarp mapping and fault trenching

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The island of Puerto Rico is located on the seismically active, northeastern part of the plate boundary separating the North America and Caribbean plates. Plate-edge deformation involves complex tectonic processes including strike-slip faulting, thrust faulting, and normal faulting. Movement on these faults produces earthquakes and tsunamis that can be hazardous for the 3.5 million U.S. citizens living in Puerto Rico. Mann and Prentice carried out fieldwork in early 2000 in western Puerto Rico to determine whether late Holocene faulting has occurred on the island. Previous workers have searched for late Holocene faults over the past 15 years but all have been unable to document faults of this age. We located one scarp cutting an alluvial fan along the southern edge of the Lajas Valley of southwestern Puerto Rico (South Lajas fault zone). We excavated a trench across this fault that revealed two surface ruptures. Radiocarbon dating of trench sediments confirmed that both ruptures have occurred over the past 7500 years. The South Lajas fault therefore becomes the first documented Holocene fault in Puerto Rico. We also located scarps in Quaternary alluvium in the Anasco Valley of western Puerto Rico which are aligned with the Cerro Goden fault zone mapped in adjacent bedrock by geologists with the U.S. Geological Survey in the 1970 s. Several promising sites for future paleoseismic studies were identified along the trace of Cerro Goden fault. Rupture of the Cerro Goden fault, which appears to diagonally cross the island of Puerto Rico, could pose a signficant hazard to Mayaguez, the largest city in western Puerto Rico and located about 10 km to the south of the Anasco Valley segment of the fault. Our studies of the location and paleoseismicity of the South Lajas and Cerro Goden faults in Puerto Rico are signficant because the island is one of the most densely populated areas of the western hemisphere and could be severely impacted by an earthquake generated by shallow surface rupture of these newly identified faults.